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DESIGN OF ENERGY HARVESTING TECHNOLOGY: FEASIBILITY FOR LOW-POWER WIRELESS SENSOR NETWORKS

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ABSTRACT

In designing for a system's lifecycle considerations, long-term energy needs often become an important limiting factor. Shifting from conventional energy sources (e.g. fossil fuels) toward renewable sources (e.g. wind and solar) has become a popular means for focusing on the lifecycle of large-scale systems like automobiles and the national electrical grid. This same shift in small, low-power systems such as sensors has the additional advantage of potentially increasing the operational life of the systems.

This paper introduces a methodology for determining the feasibility of *in situ* energy harvesting as a viable power source for a given low-power system. The method is demonstrated by considering a wireless sensor node and the specific application of monitoring the fatigue life of highway bridges, with a target operational life of ten years for the sensor node. Peak and average power requirements for wireless sensor nodes are calculated and compared to the power density available from solar, wind, and vibration energy. Energy storage is also discussed, including both disposable batteries (as the status quo with which to compare energy harvesting) and rechargeable systems (as a necessary component of the energy harvesting system).

Solar, wind, and vibration energy are all found to be feasible sources of power for this particular application. Vibration harvesting has lower power density than solar and wind harvesting, but has the advantage of being less dependent on location, more self-contained, and largely maintenance free. Energy harvesting in general only becomes attractive for projected life cycles exceeding the life of disposable batteries, which for this particular application is estimated at 4-6 years. Thus, energy harvesting is an excellent way to extend the lifespan of low-power systems where power availability is the limiting factor.

KEYWORDS

Energy harvesting, energy scavenging, renewable energy, wireless sensor networks, remote monitoring, power density, energy density, feasibility study, vibration, solar, wind, bridges, highways, transportation

1. INTRODUCTION

Power requirements can often be the limiting factor in designing for a product's lifecycle. Until recently, the two viable alternatives for power in most situations were grid power (which limited location and mobility) and batteries (which

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14. ABSTRACT

In designing for a system?s lifecycle considerations, longterm energy needs often become an important limiting factor.Shifting from conventional energy sources (e.g. fossil fuels)toward renewable sources (e.g. wind and solar) has become a popular means for focusing on the lifecycle of large-scale systems like automobiles and the national electrical grid. This same shift in small, low-power systems such as sensors has the additional advantage of potentially increasing the operational life of the systems.

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limited available power and longevity). Over the last decade, however, advancements in both low-power electronics and the efficiency of energy harvesting technology have opened the possibility of powering many low-power systems directly from the environment for extended periods of time.

One of the fastest developing applications for energy harvesting is the use of wireless sensor networks. Many processes and technologies can benefit from continual or periodic monitoring, but the locations most in need of such monitoring are often difficult, dangerous or expensive to access. Thus routing grid power or periodically replacing batteries is usually undesirable.

This paper describes a methodology for determining the feasibility for long-term energy harvesting for wireless nodes by examining peak and average power requirements under various sample rates and comparing this consumption to the power density available from various energy harvesting technologies. As an example, the power requirements for a specific wireless node are detailed and compared to the available power from selected energy harvesters.

1.1 BACKGROUND

Periodic or continual inspection is an essential part of many activities and processes (manufacturing, maintenance, etc.). We may desire to closely monitor the humidity and temperature of a manufacturing facility [1], or perhaps the vibration on a piece of machinery [2]. Sensing the temperature inside a jet engine [3] or recording the spread of corrosion on a highway bridge [4] are also typical examples. This inspection can sometimes be completed in person, but it is often far more convenient and cost-effective to use remote sensors.

For such sensors, there are two functions of particular interest. The first is how power is supplied to the system. The second is how information recorded by the sensor is transmitted to the outside world. For many years, transmission of data was limited to cables and wires, but wireless communication is now widely available. To take full advantage of wireless communication, we also need to eliminate any wiring necessary to provide power to the system. This would result in a physically independent, self-powered sensor that could be placed in a much wider variety of locations than one tethered by wires.

To supply power to the system without the assistance of wires, there are several available methods. First, all the necessary energy for the lifecycle could be stored in the system before installation (energy storage). Second, energy could be transmitted wirelessly to the system from a source, such as using induction or EM radiation. Third, energy could be generated or harvested *in situ* by the system from its surrounding environment (energy harvesting). This paper will focus primarily on energy harvesting, with some discussion of energy storage as well.

1.2 SPECIFIC APPLICATION

In this paper, we will consider a sensor network used to measure strain, vibration, and crack propagation in highway bridges. Because of the growing age of the American infrastructure [5-7] and the recent collapse of the I-35W Bridge in Minneapolis [8], the use of wireless sensors to continually monitor bridges is receiving increased attention. These sensors would be placed in locations on the bridge where they would be difficult, expensive, or impractical to access. Such locations may include the underside of the deck, the inside of hollow girders, or trusses high above traffic. Because of this, it is essential that the power source for the nodes be able to supply the necessary power levels for years at a time. A target lifespan of 10 years of maintenance-free operation is desired.

2. DESIGN FEASIBILITY METHODOLOGY

The methodology followed in this paper is shown in Fig 1. The first step is to specify the specific application for the wireless sensors. Then, we must specify what parameters need to be monitored and how frequently the node will perform such functions as taking measurements, processing data, performing calculations, transmitting data, etc. A specific wireless sensor system must be specified, and the power requirements for the chosen duty cycles must be calculated. We can then compare these power requirements to the available power densities of various energy harvesters. In determining harvester power densities, we must first estimate the available power in the environment (i.e. vibration signatures, solar irradiation, wind speed) and then calculate the power that the harvester can supply to the sensor node. Finally, the possible need for energy storage should be addressed, and the system can be finalized.

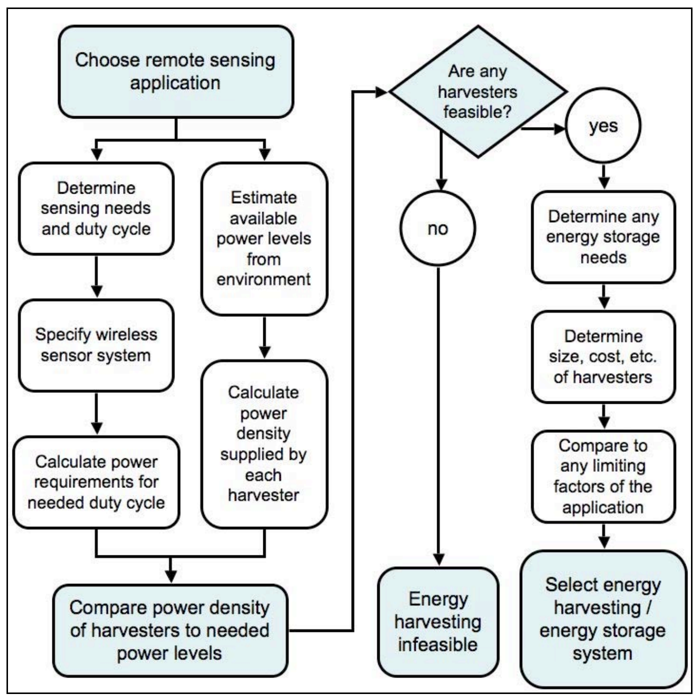

Figure 1. Feasibility methodology for using energy harvesting in WSN applications

2.1 POWER REQUIREMENTS

Following the methodology described above, we determine the power requirements for the system by (a) specifying the sampling and transmission rates for the sensor node, (b) determining the rated power consumption for a specific example sensor system, and (c) calculating the peak and average power consumption at the desired duty cycle.

2.1.1 SENSING NEEDS AND DESIRED DUTY CYCLES

When monitoring a structure such as a bridge, a variety of sensing needs may exist. For example, to measure long-term strain or crack propagation, it may be appropriate to take a sample periodically at a rate of once per hour, day, or even month. On the other hand, to measure vibration signatures or continuous strain energy, it may be more appropriate to sample in real-time at tens of hertz. Finally, some of the nodes may need to be active all the time so they can act as routers, passing information from low-power end nodes back through the network to the data processing or storage.

We will examine the power requirements for a sample wireless sensor node at the following duty cycles:

- Router mode (radio always on)
- 30 Hz sampling, with radio transmission hourly
- One sample and radio transmission per second
- One sample and transmission per minute
- One sample and transmission per hour
- One sample and transmission per day

One sample and transmission per month

External sensors will also require power during each sample cycle. However, in some cases, this additional load can be neglected. For example, one typical sensor configuration is four strain gauges arranged in a Wheatstone bridge. By using high resistance strain gauges, a low supply voltage, and a very brief sample pulse, the power draw can be minimized. Using four 1 kΩ gauges, a supply voltage of 2 V, and sample duration of 1 ms, the additional load would be 4 mW during the 1 ms pulse. For a 60 second sample interval, this sensor load only adds 4 μW to the average power each cycle, which as we will see is less than 1% of the overall power required by the wireless node at that sample interval. In this paper, we will only consider the power requirements of the wireless node itself, with the understanding that the additional needs of specific sensors can easily be added to the analysis once they are known.

2.1.2 RATED POWER DRAW OF EXAMPLE SYSTEM

The example wireless sensor node chosen for this paper is best run from either a 24 V DC source or from 4 AA batteries (6 V DC, total). A manufacturer may give typical power consumption at two duty cycles: one sample every second and one sample every 60 seconds (Table 1).

Table 1. Rated power consumption of example node

	1 sample / second	1 sample / minute
6 V DC Input	13.3 mW	0.5 mW
24 V DC Input	33 mW	16 mW

Naturally, for our specific application, we will want to minimize the power draw, so we would want to use the lower voltage. The node is actually capable of performing with an input voltage of as low as 3.6 V with customization, but for the sake of consistency we will use a standard input of 6 V DC throughout the remainder of the paper.

Figure 2 shows a waveform of the instantaneous power consumption during a sample cycle, using 6 V battery power and a 1 second sample interval (Fig. 2). The power usage is broken down by activity in Table 2.

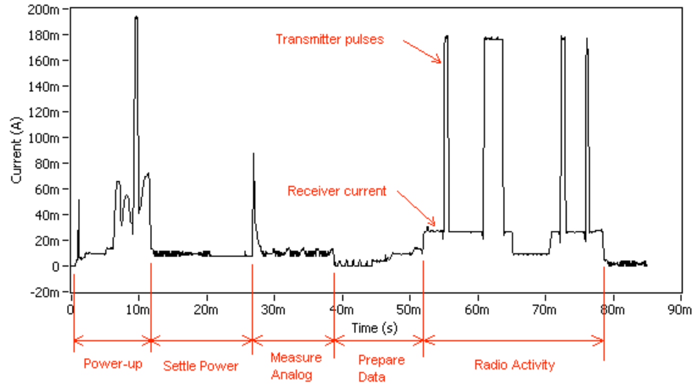

Figure 2. Waveform of power consumption during sampling

Table 2. Break-down of power consumption

Function	Power (mW)	Δt (ms)
Power-up	200	12.4
Settle power	52.5	14.5
Measure analog	73.4	13.0
Prepare data	37.9	12.0
Radio activity (transmit data/ack data)	207	29.0
Total – active period	154 (average)	81
Sleep period	0.3	variable

2.1.3 POWER DRAW AT DESIRED DUTY CYCLES

With the power consumption for each activity in the sample cycle known, we can extrapolate the overall power draw over different sample periods as well. We assume for these calculations that for typical operation, where each sample cycle includes both a measurement and a radio transmission, the waveform for the active period remains the same, with the duration of the sleep period the only change. Table 3 shows an example of this calculation, where an hourly sample rate is considered.

In this scenario, the average power draw is approaching the lower bound of 0.3 mW imposed by the level of power needed for the current “sleep” mode. Increasing the time between samples beyond this point will not yield any further energy savings. To decrease the average power required, we must now focus on decreasing the power level while the system is idle.

Table 3. Power consumption at 1 sample per hour

Function	Power (mW)	Energy (mJ)	Δt (ms)
Power-up	200	2.5	12.4
Settle power	52.5	0.8	14.5
Measure analog	73.4	1.0	13.0
Prepare data	37.9	0.5	12.0
Radio activity	207	6.0	29.0
Sleep period	0.3	1,008.0	3,599,919
Complete Cycle	0.3	1,018.6	3,600,000

By reprogramming the node, we may be able to put it in a "deep sleep" mode with far less power draw than its current configuration. For comparison, the Ambiomote24 [9] is a similar system that can go into a deep-sleep mode consuming only 9 μW [10]. If a similar result could be obtained with the example node, the overall power consumption would approach this new limit with sample intervals of a day or more. Completely turning off the module between samples would result in even more energy savings. However, it is more likely that some functions, like the clock, would need to be on continually to ensure proper timing of the samples.

In some instances, it may be necessary to take measurements more frequently than once per second or minute. To measure vibration, cyclical stress, and other time-dependent characteristics, we would want to record continuously for an extended period of time. As an example, we may want to take samples at a rate of 30 Hz, and then send a sum or other data analysis or transformation once per hour. The power consumption in this case is outlined in Table 4.

Table 4. Sampling at 30 Hz, then transmitting once per hour

Function	Power (mW)	Energy (mJ)	Δt (ms)
Power-up	200	N/A	N/A
Settle power	52.5	115,288	2,195,959
Measure analog	73.4	103,054	1,404,000
Prepare data	37.9	0.5	12.0
Radio activity	207	6.0	29.0
Sleep period	0.3	N/A	N/A
Complete Cycle	60.7	218,348	3,600,000

In this case, the node spends a large part of the cycle measuring data. There is not enough extra time to cycle through the sleep/power-up functions repeatedly, so the node spends most of the rest of the time in the "settle power" function. At the end of each hour, the node prepares the data and sends a single data transmission. This scenario results in an overall power consumption of 60.7 mW, much higher than our calculations for previous sample rates.

The average power consumption for a variety of sample rates (including the ones discussed) is shown in Fig. 3. Each sample rate has three bars showing scenarios where (a) the node uses its current configuration of staying on and consuming 0.3 mW when idle, (b) the node is able to enter a "deep-sleep" mode that only consumes 9 μW, and (c) the node is able to turn completely off between samples and consumes no power. In addition to the sample rates described previously, the chart includes a router mode, where the radio is transmitting continuously, and sample rates of once per day and once per month.

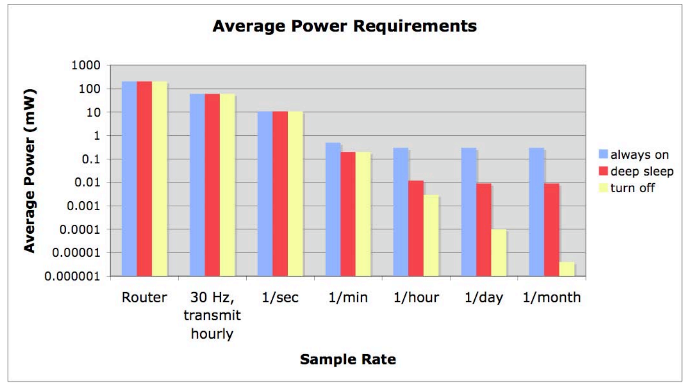

Figure 3. Average power consumption by sample rate

Considering this information from a different perspective, it can be translated into the equivalent energy consumption for one year of operation. Figure 4 shows the energy required for each scenario. In this figure, the 30 Hz sample rate is examined in two ways. Continuous monitoring throughout the entire year will usually not be necessary. Instead, the node may monitor continuously for a limited amount of time, then operate at a lower sample rate the remainder of the year. In Fig. 4, numbers are given for the scenarios of (a) running at 30 Hz for 10 weeks, then at once per hour the rest of the year, and (b) running at 30 Hz for 2 weeks, then hourly for the remainder.

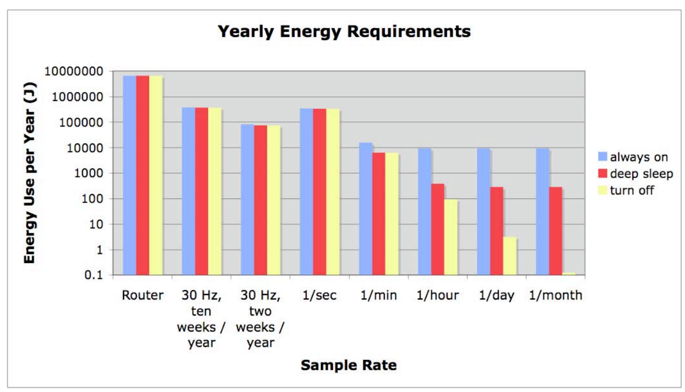

Figure 4. Yearly energy consumption by sample rate

The power and energy consumption of each sample rate is shown more fully in Appendix A. We can see that there is a wide range of power levels necessary for different sample rates, from about 200 mW to operate as a router on the high end to 0.3 mW and possibly even lower as the sample rate decreases. To examine the feasibility of powering this node with energy harvesting technology, we will focus on three scenarios: the router mode (high power), running at 30 Hz for 10 weeks and once per hour the rest of the year (medium power), and sampling once per day with a deep sleep mode (low power).

The power and energy requirements for these three scenarios are summarized in Table 5.

Table 5. Power and energy consumption for test scenarios

Scenario	Average Power	Yearly Energy	
Router mode (radio always on)	207 mW	6.53 MJ	1.81 kWh
30 Hz (10 weeks) / hourly rest of year	60.7 mW (30Hz) 300 μW (hourly)	375 kJ	104 Wh
One sample / day (with deep sleep)	9 μW	284 J	78.8 mWh

2.2 ENERGY HARVESTING TYPES

With a better understanding of the power needs of the system, we can compare this to the power supplied by each energy harvester. Many technologies exist to scavenge energy from the surroundings. We consider three of the most common and well developed: photovoltaic cells, wind turbines, and vibration harvesters.

2.2.1 SOLAR ENERGY: PHOTOVOLTAIC CELLS

Solar energy is becoming a reliable alternative to batteries or grid power in many applications. Solar-powered sensors have recently been installed on bridges in Corinth, Greece and New London, Connecticut [11]. Photovoltaic cells are the most common method for capturing solar energy, with higher power density than most other energy harvesting technologies [12].

The theoretical power available from a PV cell can be determined from the light irradiance available (E, in watts per square meter), the area of the cell (A_{cell}, in square meters), and its energy conversion efficiency (η):

$$P_{\max} = \eta E A_{cell}$$

The standard test conditions for measuring efficiency is an irradiance of 1,000 W/m^2, typical for much of the U.S. on a sunny day [13]. Efficiencies can range from 5% to 40% [14], with most commercially available cells falling around 8-15%. For a cell with 10% efficiency, this translates into an approximate power density of 100 W/m^2, or 10 mW/cm^2.

Of course, the sunlight available varies throughout the day and the year. Solar insolation equates the actual sunlight available during the day to an equivalent number of hours at peak irradiance. For example, Austin, Texas has an insolation of 5.88 hours/day during the summer and 4.65 hours/day during the winter [15]. Combining the winter insolation with the previous calculation, a solar cell with 10% efficiency would be able to provide a yearly average of at least 1.9 mW/cm^2. This translates into a yearly energy production in the range 60 kJ (17 Wh) per square centimeter.

Comparing this energy production to the three duty cycle scenarios listed in Table 5, we find that the low-power configuration could easily be run continuously from even one square centimeter of PV paneling, provided it received direct sunlight and had sufficient energy storage to power the sensor through the night. To power the 30 Hz duty cycle continuously would require at least 32 cm^2, but because the duty cycle is only needed for part of the year, a panel much smaller could be used and excess energy stored. To run the sensor in router mode, a panel of at least 110 cm^2 and direct sunlight would be required.

Because of the constraints in location on the bridge, it is highly likely that PV panels would not be exposed to direct sunlight the entire day. Unless a tracking system is included in the hardware, the panels would, at best, receive full sunlight at varying angles throughout the day, with many installations encountering shade for at least part of the day as well. Solar irradiance in the shade is in the neighborhood of 50-100 W/m^2, meaning that the power out could be cut by a factor of ten to twenty. This would necessitate the use of larger panels (up to 1000 cm^2, or 1 ft^2), but even these would be well within the feasible scope for use on bridges.

2.2.2 WIND ENERGY: TURBINES

The theoretical power available from a wind turbine can be determined from the air density (ρ), turbine area (S), intake air velocity (v_1), and the coefficient of performance (C_p):

$$P = \tfrac{1}{2}\rho S v_1^{3} C_p$$

The theoretical maximum to the coefficient of performance, known as the Betz Limit, is 0.593. Many commercial products have coefficients in the range of 0.3-0.5. As is evident by the governing equation, the power is proportional to the cube of the wind speed, meaning that a great deal more power is available at higher velocities than lower velocities. If we were to use a coefficient of 0.3, the power density of a turbine at an air velocity of 2 m/s (4 mph) would be only 0.14 mW/cm^2, but a velocity of 5 m/s (11 mph) would yield 2.25 mW/cm^2, and 10 m/s (22 mph) would yield 18 mW/cm^2. Figure 5 shows the relationship between wind speed and output power, again assuming a coefficient of performance of 0.3.

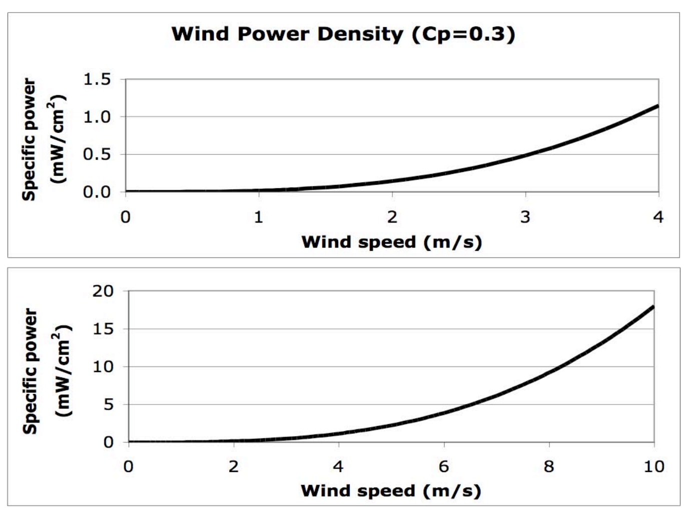

Figure 5. Power density of turbine by wind speed

This result is highly dependent on the constancy of the wind in the area of interest. Studies of one bridge at multiple points and elevations revealed a distribution peaking at 5 m/s, with speeds generally between 2 and 15 m/s [16]. On the other hand, studies of several micro-turbines installed in initially promising locations showed the same distribution when there was wind, but the turbines were also idle 30-70% of the time [17].

If, for simplicity, we assumed a relatively constant wind speed of 5 m/s and a coefficient of performance of 0.3, the power density available from a wind turbine would be 2.25 mW/cm^2. Thus a turbine as small as 1 cm^2 would theoretically be sufficient to power either of the lower-power duty cycles, and a turbine of 92 cm^2 (14 in^2) at constant speed could power the node in router mode. Naturally, due to both practicality and the unpredictability of wind patterns, a larger turbine size than one square centimeter would be desired. Even a turbine significantly larger would still be quite feasible for use in a bridge environment.

2.2.3 VIBRATION ENERGY: PIEZOELECTRIC & INDUCTIVE HARVESTERS

The theoretical power available from vibration relates to the kinetic energy of moving masses, but the governing equations can vary depending on the mechanics and the geometry of the system. One governing equation for a cantilever beam embedded with piezoelectric material [18] involves the proof mass (m), the acceleration involved (A), the vibrating frequency (ω), and the coefficients for mechanical and electrical damping (ζ_M and ζ_E):

$$P = \frac{m\zeta_E A^2}{4\omega\left(\zeta_E + \zeta_M\right)^2}$$

As this equation shows, we can maximize power by increasing the mass of the vibrating tip, increasing the acceleration it experiences, and working in lower frequencies. This relationship also assumes the system has been tuned to resonate at the same frequency it experiences.

Several ready-to-install vibration harvesters are available, but most of them are tuned to frequencies higher than what are predominant on a bridge. The Perpetuum PMG27 [19] is tuned to 17 Hz. With a continuous vibration of 0.05 g (0.5 m/s^2), this system can generate 4 mW. With a continuous vibration at 1 g (9.8 m/s^2), the power increases to 90 mW.

Vibration on a bridge is frequently lower, in the range of just a few hertz, with maximum accelerations from 0.05 g to 1.5 g. By taking advantage of the additional power available at low frequencies and increasing the proof mass, a similar system should be capable of powering the wireless node even with intermittent traffic. As an example of feasible vibration harvesting for bridge monitoring, Clarkson University installed a wireless node powered by an inductive (magnet and coil) vibration harvester on a rural bridge in New York in 2007 [20]. Even with sporadic traffic patterns and prototype equipment, they were able to take measurements about five to ten times an hour during the day (the system was programmed to immediately take a sample if it had enough power to do so, instead of storing energy for later use, thus the sample rate was much lower during the night).

2.3 ENERGY HARVESTING DISCUSSION

Initial analysis shows that all three energy-harvesting techniques considered are feasible for powering wireless nodes for a bridge sensor network. Of the three, solar and wind power are more developed and in use commercially, while vibration is still largely in the research phase (although many commercial products are beginning to be available).

Both solar and wind are similar in their power densities during optimal conditions (i.e. direct sunlight, constant wind), but die off quickly where light or wind is of low magnitude or inconsistent. In addition, they also both must include exposed parts (i.e. PV panels, turbine blades) that may require careful design, blending with the surrounding environment, and occasional maintenance or cleaning. This is especially true in the harsh environment of a roadway, where oil, grime, animal droppings, garbage, vandalism, and severe weather may pose a danger.

Vibration harvesting systems, in contrast, are largely maintenance-free and can be entirely isolated from the environment. However, they typically can only operate over a short range of frequencies, which can vary from bridge to bridge. They also are currently more expensive than solar or wind systems. A large portion of this cost is the power processing of the generated AC electricity into a steady DC voltage capable of powering the system or charging a battery.

Because all three technologies are shown to be feasible for this application and their unique strengths make them more appropriate in different scenarios, all three should be developed for further consideration.

2.4 ENERGY STORAGE TYPES

Remote monitors must be able to perform as needed throughout their lifecycle, without suddenly running out of power at a critical moment. Because of this need, energy storage is a vital component of the overall design. Energy storage can be used in two ways. First, the designer may simply include enough stored energy at the outset to last the entire life of the system, or at least until it can be conveniently replaced manually. Alternatively, the designer may incorporate a rechargeable system that is replenished periodically or continually. The first approach is that of primary (one-time-use) batteries, which is currently the industry standard for wireless systems. The second approach is that of rechargeable storage, such as rechargeable batteries, capacitors, and fuel cells. This section will briefly touch upon how each of these approaches influences the feasibility of energy harvesting in our design.

2.4.1 PRIMARY (DISPOSABLE) BATTERIES

Energy harvesting is only attractive if it compares favorably to the alternative means of powering the system. For

a sensor network where wired power from the grid is not desired, battery power is, by far, the primary source of power. Such batteries may be replaceable by the user, or they may be designed to last the life of the product and then disposed of together. Disposable batteries are relatively inexpensive, and their standardization makes them very convenient. Their predicted shelf life, energy capacity, and discharge rates make them easy to design around. As mentioned before, the example sensor node considered for this paper is designed to use four AA batteries. If energy harvesting does not show some advantage over disposable batteries, then there is no reason to consider them further.

The most widespread type of primary battery is the alkaline battery. The Energizer E91 battery (AA, alkaline) is rated at a capacity of 2.8 Ah when discharged from 1.5 V to 0.8 V at a constant 25 mA [21]. Total capacity for four batteries would be 16.8 Wh. This would theoretically power the sensor in router mode for 3 days, in the 30 Hz/hourly scenario for 4-5 years, and in the deep-sleep mode for up to 7 years (limited by the battery's shelf life). The actual usable capacity is slightly lower, because the voltage drops as the batteries discharge. However, a life of 2-4 years seems a reasonable estimate for this system under the lower-power duty cycles.

A better choice for a primary battery would be the lithium iron disulfide battery, marketed by Energizer simply as "lithium." Compared to alkaline, lithium has a longer shelf life (16 years vs. 7 years) and lower self-discharge rate (0.6% per year vs. 3%) [22]. Lithium batteries also have greater energy capacity than alkaline: 3.2 Ah, for a total of 19.2 Wh for four batteries. Lithium batteries would power the node for at medium power for 4-6 years. If the deep-sleep mode is possible, a life in excess of 10 years may be possible.

Because of the success already available with primary batteries and their low cost relative to many energy harvesting systems, energy harvesting may not be needed for shorter lifecycles or if the power requirements can be reduced sufficiently. Three scenarios do present themselves where energy harvesting would be appropriate:

- The required power level is larger than that available from batteries, but still within the scope of energy harvesting (such as the wireless node in router mode).
- The desired lifetime is much longer than what is available from primary batteries, due to the limited energy capacity and shelf life.
- Energy harvesting can be accomplished in a way that the overall cost over the lifetime of the product is less expensive than the cost of using primary batteries.

2.4.2 RECHARGEABLE ENERGY STORAGE

Regardless of the means of energy harvesting selected, the system will most likely include some means of rechargeable energy storage. This storage serves third functions. First, it allows a steady, well-conditioned flow of electricity to the system, instead of the noisy, variable power generated from the environment. Second, it allows excess energy from peak generation to be stored for use when generated power falls below the level required by the system, such as at night. Third, it allows the peak power draw to be greater than what may be available from the harvested energy rates.

A wide variety of rechargeable solutions are available, such as rechargeable batteries (Lead acid, NiCd, NiMH, Li ion, etc.), capacitors, fuel cells, and hybrids of these categories (e.g. ultracapacitors). Lithium ion batteries are widely used for similar applications [23,24], but many options may be most appropriate for a given application. In selecting a rechargeable energy storage system, the following must be considered:

- The life of the energy storage, as well as the harvester, must meet the desired operational life for the system.
- The energy capacity must be able to supply continuous power through the longest expected length of time where energy harvesting will be unavailable (e.g. bad weather for several weeks).
- The voltage of the energy storage must be appropriate to both power the wireless node and be charged by the generated power from the harvester.
- The maximum level of current (or power) available from storage must exceed the peak current (or power) required by the node.
- The energy storage system must be designed appropriate to the challenges and constraints of the application, including temperature, humidity, possible impact, etc.
- The energy storage system must meet the designer's needs for lifecycle considerations, including a means of safe disposal or recycling at the end of life.

3. GENERAL DISCUSSION AND CONCLUSION

This paper presents a methodology for determining the feasibility of energy harvesting for wireless sensor networks. Following the methodology (outlined in Section 2), we were able to determine the feasibility of energy harvesting for the particular application of monitoring bridge health with a specific example wireless sensor node. All three energy-harvesting technologies considered (photovoltaic cells, wind turbines, and vibration harvesters) have sufficient power density to feasibly drive the sensor node at the desired duty cycles within the constraints of a bridge environment.

Solar, wind, and vibration harvesting each have different strengths, and each is best suited to different situations. In fact, different types of harvesters may be appropriate even for sensors on different parts of the same bridge. It is recommended that all three technologies be developed, so that the optimal technology can be used for any bridge and sensor.

For the example wireless node considered, primary (disposable) batteries may already give a life in the neighborhood of five years in the node's current configuration, and possibly in excess of ten years if the power requirements are drastically reduced. However, energy harvesting remains a promising alternative to extend the operational lifespan and allow operation at higher power levels.

This same methodology can easily be used to determine the feasibility of energy harvesting for any wireless sensor application, as well as many other applications where the long-

term power requirements and the energy levels available from the environment can be reliably estimated. After calculating the size of energy harvesting system needed to supply the power, this hypothetical system can be compared to the constraints of the application, and if still feasible, the different means of powering the system can then be compared on other characteristics, such as cost, maintenance needs, reliability, etc. The system can be designed with the power needs of the entire lifecycle in mind, using energy harvesting as a feasible, reliable, renewable source of energy.

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APPENDIX A: POWER / ENERGY REQUIREMENTS BY DUTY CYCLE

Average Power (mW)			
Duty Cycle	*Always on*	*Deep sleep*	*Shut down*
Router mode	207	207	207
100 Hz sampling, hourly transmission	73.4	73.4	73.4
30 Hz sampling, hourly transmission	60.7	60.7	60.7
1 sample/second	10.9	10.7	10.7
1 sample /minute	0.5	0.2	0.2
1 sample /hour	0.3	0.007	0.003
1 sample /day	0.3	0.009	0.0001
1 sample /month	0.3	0.009	0.000004

Yearly Energy Usage (J / year)			
Duty Cycle	*Always on*	*Deep sleep*	*Shut down*
Router mode	6,527,952	6,527,952	6,527,952
100 Hz for 10 weeks, daily for 42 weeks	451,570	444,229	444,000
100 Hz for 2 weeks, daily for 50 weeks	97,883	89,149	88,876
30 Hz for 10 weeks, daily for 42 weeks	374,760	367,419	367,190
30 Hz for 2 weeks, daily for 50 weeks	82,521	73,787	73,514
1 sample/second	343,742	337,435	337,435
1 sample /minute	15,768	6,307	6,307
1 sample /hour	9,460	221	95
1 sample /day	9,460	284	3
1 sample /month	9,460	284	0.1